# NeXSPheRIO Results on Elliptic-Flow Fluctuations at RHIC

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By using the NexSPheRIO code, we study the elliptic-flow fluctuations in Au+Au collisions at $200\,A\,\mathrm{GeV}$. It is shown that, by fixing the parameters of the model to correctly reproduce the charged pseudo-rapidity and the transverse-momentum distributions, reasonable agreement of $< v_2 >$ with data is obtained, both as function of pseudo-rapidity as well as of transverse momentum, for charged particles. Our results on elliptic-flow fluctuations are in good agreement with the recently measured data on experiments.

## 1. INTRODUCTION

It is by now widely accepted that hydrodynamics is a successful approach for describing the collective flow in high-energy nuclear collisions. The basic assumption in hydrodynamical models is the local thermal equilibrium. It is assumed that, after a complex process involving microscopic collisions of nuclear constituents, at a certain early instant a hot and dense matter is formed, which would be in local thermal equilibrium. After this instant, the system would evolve hydrodynamically, following the well known set of differential equations.

However, since our systems are not large enough, important event-by-event fluctuations are expected. With regard to this question, fluctuation in the initial conditions deserves a special consideration. Because the incident nuclei are not smooth objects, if thermalization is verified at very early time as usually assumed in hydrodynamic approach, the initial conditions for hydrodynamics, expressed by distributions of velocity and thermodynamic quantities at such an instant, could not be smooth and would fluctuate from event to event.

In the past few years, we have studied several effects caused by such fluctuating and

non-smooth initial conditions on some observables, by using a code especially developed for this purpose, which we call NeXSPheRIO [1–5]. In particular, we showed in preliminary works on Au+Au collisions at $130A\,$GeV that fluctuations of $v_2$ are quite large [1]. Recently, $\sigma_{v_2}/\langle v_2\rangle$ data were obtained in $200\,A\,$GeV Au+Au collisions [6–8], showing a good agreement with our previous results, when QGP is included. The main object of this communication is to check it at the correct energy and with a more updated version of the code.

In what follows, we will first give a brief description of the NeXSPheRIO code. This will be done in the next Section. Then, we explain in Section 3 how this code is used to compute the observables of our interest. We show the results of computations in Section 4 where effects of fluctuations in the initial conditions are emphasized. Finally, conclusions are drawn and further outlook are given.

## 2. NEXSPHERIO CODE

NeXSPheRIO is a junction of two codes: NeXus and SPheRIO. The NeXus code [9] is used to compute the initial conditions (IC) $T^{\mu\nu}$, $j^\mu$ and $u^\mu$ on some initial hypersurface. It is a microscopic model based on the Regge-Gribov theory and the main advantage for our purpose is that, once a pair of incident nuclei or hadrons and their incident energy are chosen, it can produce, in the event-by-event basis, detailed space distributions of energy-momentum tensor, baryon-number, strangeness and charge densities, at a given initial time $\tau=\sqrt{t^2-z^2}\sim 1\,$fm. Remark that, when we use a microscopic model to create a set of IC for hydrodynamics, the energy-momentum tensor produced by the microscopic model does not necessarily correspond to that of local equilibrium, so we need to transform it to that of the equilibrated matter, adopting some procedure as described in detail in Ref. [10].

We show in Fig. 1 an example of such a fluctuating event, produced by NeXus event generator, for central Au + Au collision at $130\,A\,$GeV, compared with an average over 30 events. As can be seen, the energy-density distribution for a single event (left), at the mid-rapidity plane, presents several blobs of high-density matter, whereas in the averaged IC (right) the distribution is smoothed out, even though the number of events is only 30. The latter would corresponds to the usually adopted smooth and symmetrical IC in many hydrodynamic calculations. The bumpy event structure, as exihibited in Fig. 1, was also shown in calculations with HIJING [11]. As already observed there and studied in [1–5, 10]

this bumpy structure gives important consequences in the observables.

Solving the hydrodynamic equations for events, so irregular as the one shown in Fig 1, requires a special care. The SPheRIO code is well suited to computing the hydrodynamical evolution of such systems. It is based on Smoothed Particle Hydrodynamics (SPH), a method originally developed in astrophysics [12] and adapted to relativistic heavy ion collisions [13]. It parametrizes the flow in terms of discrete Lagrangian coordinates attached to small volumes (called "particles") with some conserved quantities. Its main advantage is that any geometry in the initial conditions can be incorporated and giving a desired precision.

Now, we have to specify some equation of state (EoS) describing the locally equilibrated matter. Here, in accordance with Ref. [4], we will adopt a phenomenological implementation of EoS, giving a critical end point in the QGP-hadron gas transition line, as suggested by the lattice QCD [14].

Although too simplified, we shall neglect in the following any dissipative effects and also assume the usual sudden freezeout at a constant temperature. As for the conserved quantities, besides the energy, momentum and entropy, we consider just the baryon number.

In computing several observables, NeXSPheRIO described here is run many times, corresponding to many different events or initial conditions. At the end, an average over final results is performed. We believe that this mimics more closely the experimental conditions, as compared to the canonical approach where usually smooth initial conditions for just one (averaged) event are adjusted to reproduce some selected data.

## 3. ADJUSTING THE PARAMETERS OF THE MODEL

Having been depicted our tool, let us now explain how we fix the parameters of the model and compute the observables of our interest.

First of all, since it is impossible to know the impact parameter in experiments, we use some quantity which in principle can be experimentally determined to define the centrality. For instance, in our code, it is possible to determine the number of participant nucleons in each event which is intimately connected to the often used ZDC energy. Although the participant number is closely related to the impact parameter, it is not the same [3] due to fluctuations.

Now, certainly any model to be considered as such should reproduce the most funda-

mental, global quantities involving the class of phenomena for which it is proposed. So, we begin by fixing the initial conditions so as to reproduce properly the (pseudo-)rapidity distributions of charged particles in each centrality window. This is done by applying an $\eta$-dependent factor $\sim 1$ to the initial energy density distribution of all the events of each centrality class, produced by NeXus. Examples of such factors are shown in Fig. 2 for the centrality (15 - 25)% class both for fluctuating IC and the averaged IC. We show the resultant pseudo-rapidity distributions in Fig. 3. Here, *without fluctuation* means that the computation has been done for one event whose IC are the average of the same 122 fluctuating IC, used in the other case, except for the normalization factor shown in Fig. 2. Results with averaged IC are being shown in comparison, to clearly exhibit the effects of fluctuating initial conditions. Observe that, to obtain the same multiplicity as shown in Fig. 3, we have to start with a smaller average energy density in the case of averaged IC, as implied by the normalization factor of Fig. 2. This is a manifestation of the effect already discussed in Ref. [10]. Another observation concerning Fig. 3 is that the freezeout temperature, $T_{fo}$, gives a negligible influence on the (pseudo-)rapidity distributions.

Next, we would like to correctly reproduce the transverse-momentum spectra of charged particles, which can be achieved by choosing an appropriate freezeout temperature, $T_{fo}$. Figure 4 shows examples of choice with the corresponding spectra. One can see in this Figure that the fluctuating IC make the transverse-momentum spectra more concave, closer to data. Also, one sees that higher freezeout temperature is required in this case, as compared to the one for averaged IC. These characteristics are consequences of the bumpy structure of the energy-density distribution, as shown in Fig. 1, because, those high-energy spots produce higher acceleration than the smooth distribution, due to a higher pressure gradient.

## 4. RESULTS

In Fig. 5, upper panel, we show the pseudo-rapidity distributions of $v_2$ for charged particles, calculated in three centrality windows as indicated. It is seen that they reasonably reproduce the overall behavior of the existing data, both the centrality and the $\eta$ dependences. The lower panel of Figure 5 shows the transverse-momentum distribution of $v_2$ in the mid-rapidity region. Again, the main feature is very well reproduced. Notice that, differently from the usual hydrodynamic calculations, the curve shows some bending at large-$p_T$

values that is due, in our opinion, to the granular structure of our initial conditions, which produces a violent isotropic expansion at the beginning, so reducing the anisotropy of large-$p_T$ components. This question is being studied more carefully.

Now, we show the results for $v_2$ fluctuations in Fig. 6. The freeze-out temperature has been chosen as explained in the previous Section and increases with the impact parameter $\langle b \rangle$ (decreases with the participant nucleon number $N_p$), or the fluid decouples hotter and hotter as one goes from more central to more peripheral collisions as expected. We remark that, also in computing the $p_T$ distribution of $v_2$ shown in Fig. 5, these values of temperature have been used and then averaged over the partial windows. The curves of $v_2$ fluctuations, plotted in Fig. 6, indicate that the NeXSPheRIO results remain in nice agreement with the data, also in the present calculation.

## 5. CONCLUSIONS

In this communication, we gave an account of a check we made of the previous results on charged $v_2$ fluctuations [1], to see whether a more careful computation at the correct energy $200\,A\,\mathrm{GeV}$ and with a more updated version of the code can still reproduce the recently measured $\sigma_{v_2}/\langle v_2 \rangle$ data [6–8].

In our model, the fluctuations of the observables appear mostly because of the initial condition fluctuations, introduced by the NeXus generator [9], with some additional small effects appearing from the freeze-out procedure with Monte-Carlo method. The latter is, however, usually made negligible with increasing Monte-Carlo events at the freezeout.

Our conclusion is that we are in the correct way, being able to reproduce the essential features of $v_2$ for charged particles, and our previous prediction for $v_2$ fluctuations, with QGP introduced, remain valid for $200\,A\,\mathrm{GeV}$ Au+Au collisions.

As mentioned in the previous Section, we are further studying in more detail effects of inhomogeneity of the initial conditions on $v_2$. Another study in progress is the effects of continuous emission instead of sudden freezeout.

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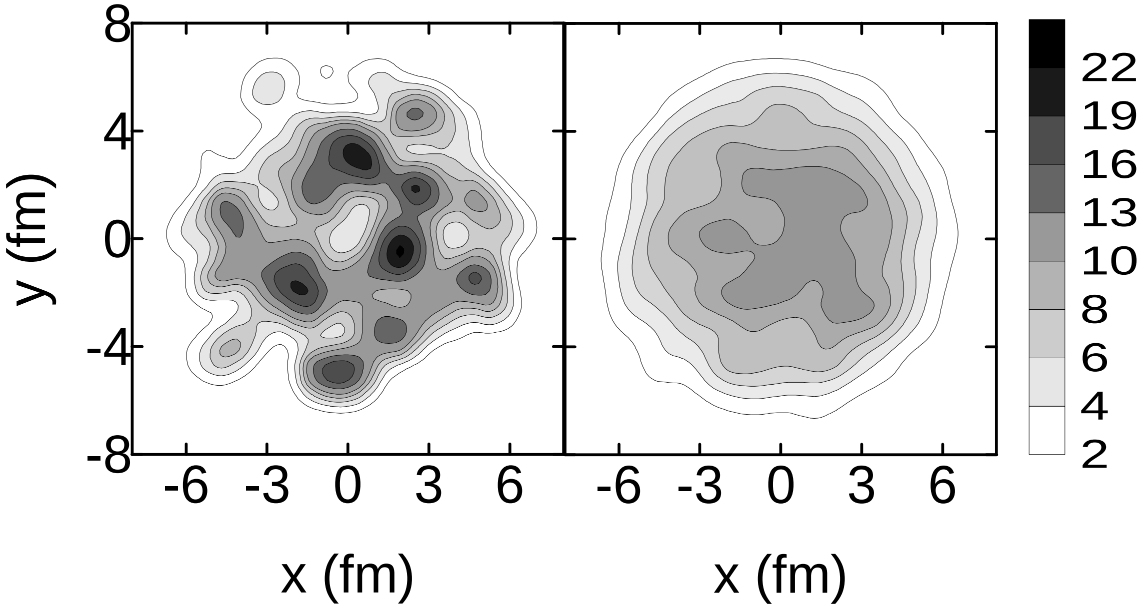


**Figure 1.** Examples of initial conditions for central Au+Au collisions given by NeXus at mid-rapidity plane. The energy density is plotted in units of GeV/fm$^3$. Left: one random event. Right: average over 30 random events (corresponding to the smooth initial conditions in the usual hydro approach).

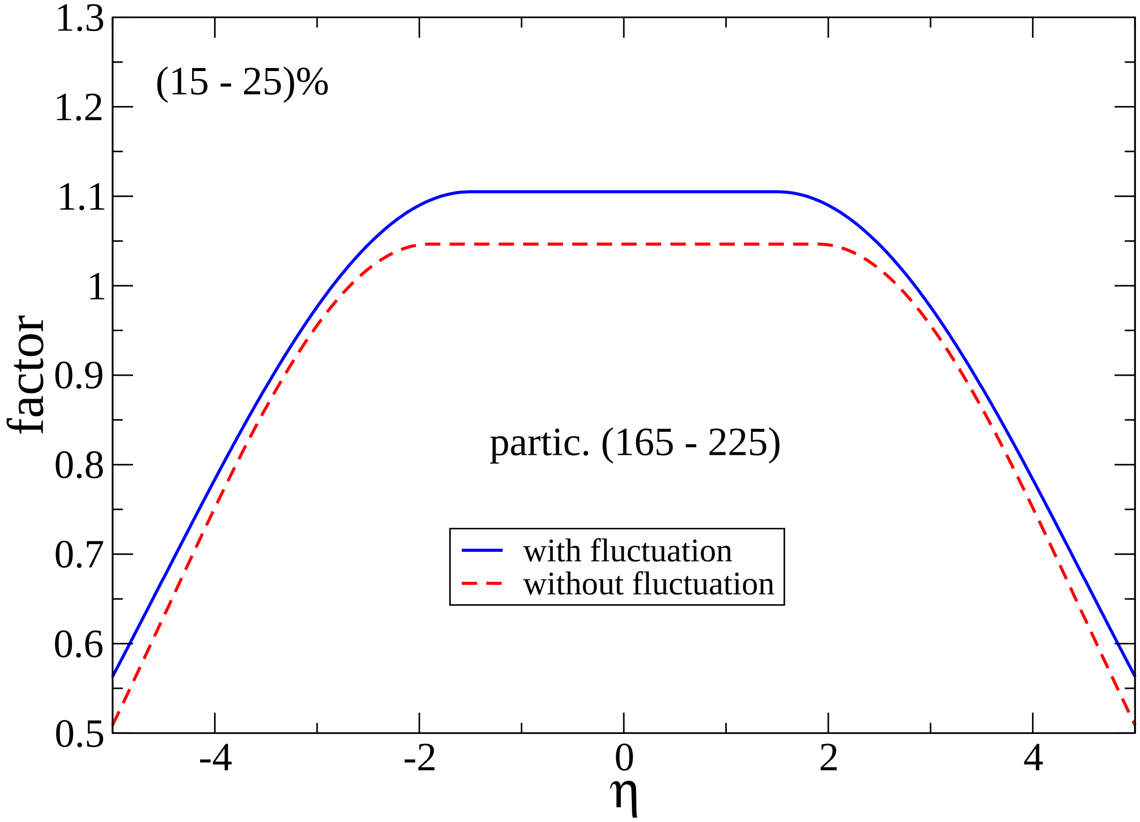


**Figure 2.** Example of $\eta$-dependent factor which was used to multiply the energy density given by NeXus in the initial conditions of each event.

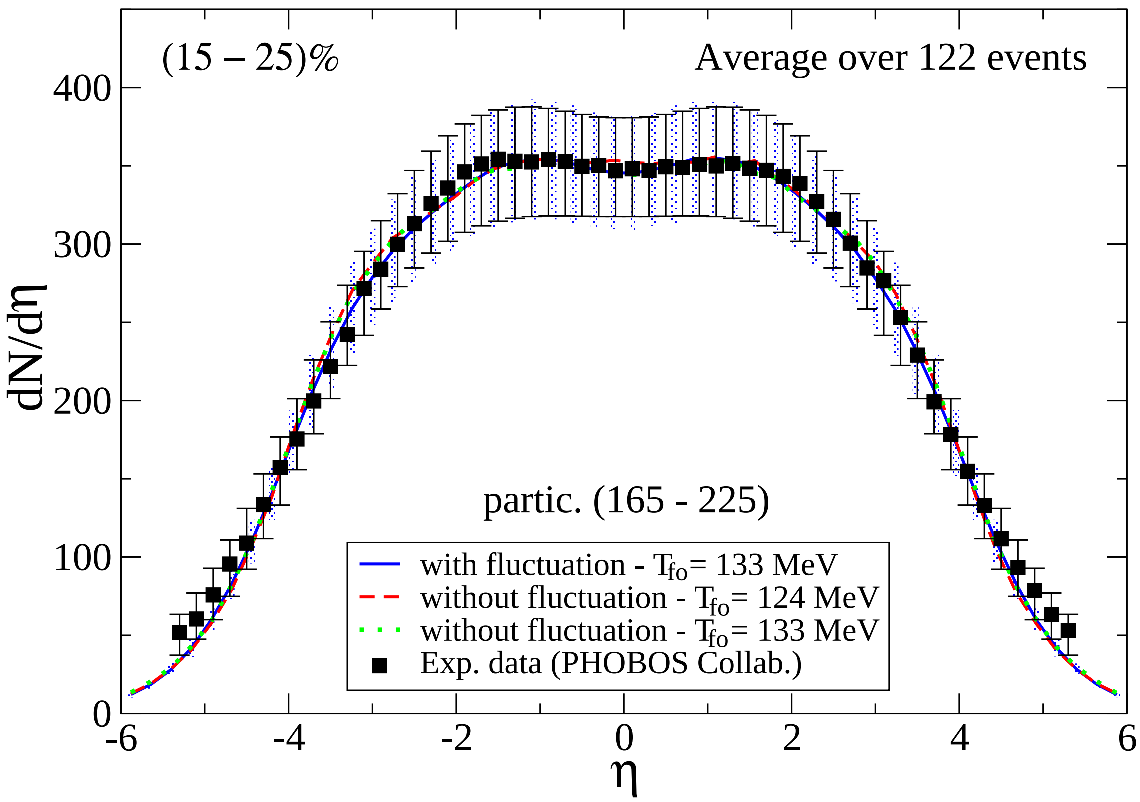


**Figure 3.** Results of pseudo-rapidity distributions calculated with the NeXus initial conditions as explained in the text. PHOBOS data [15] are shown for comparison.

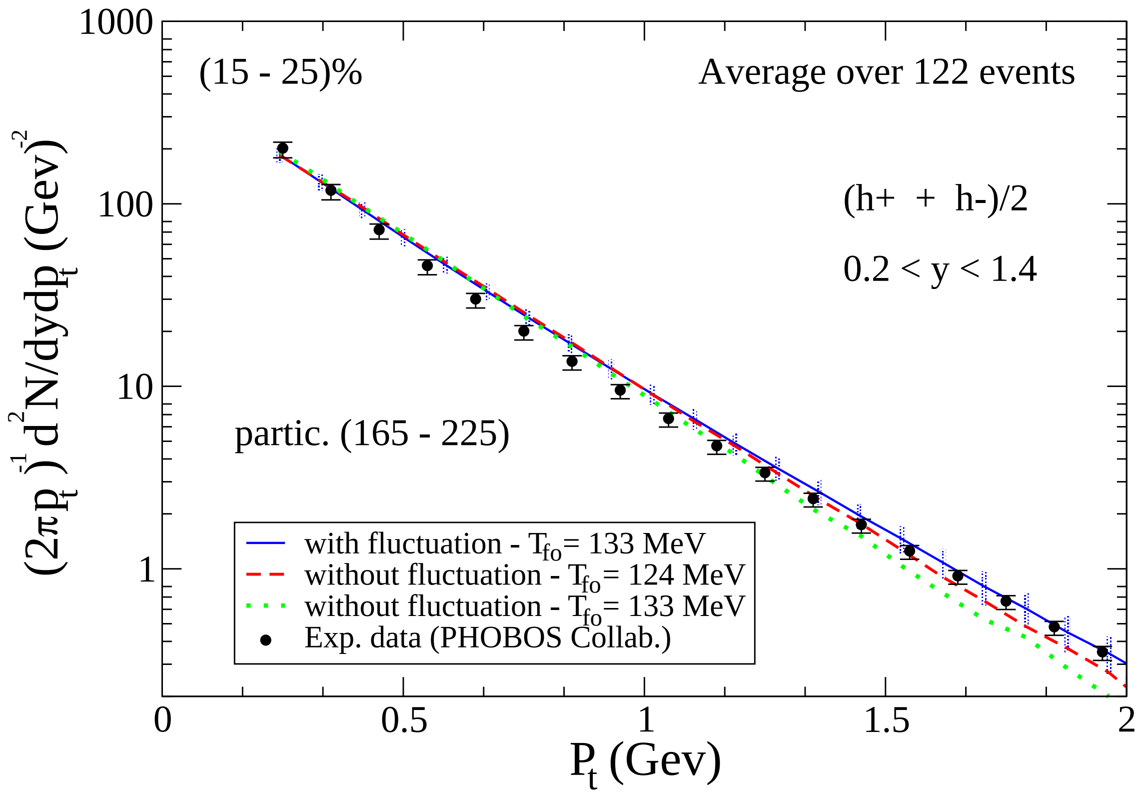


**Figure 4.** Results of transverse-momentum distributions calculated with the NeXus initial conditions as explained in the text. PHOBOS data [16] are shown for comparison.

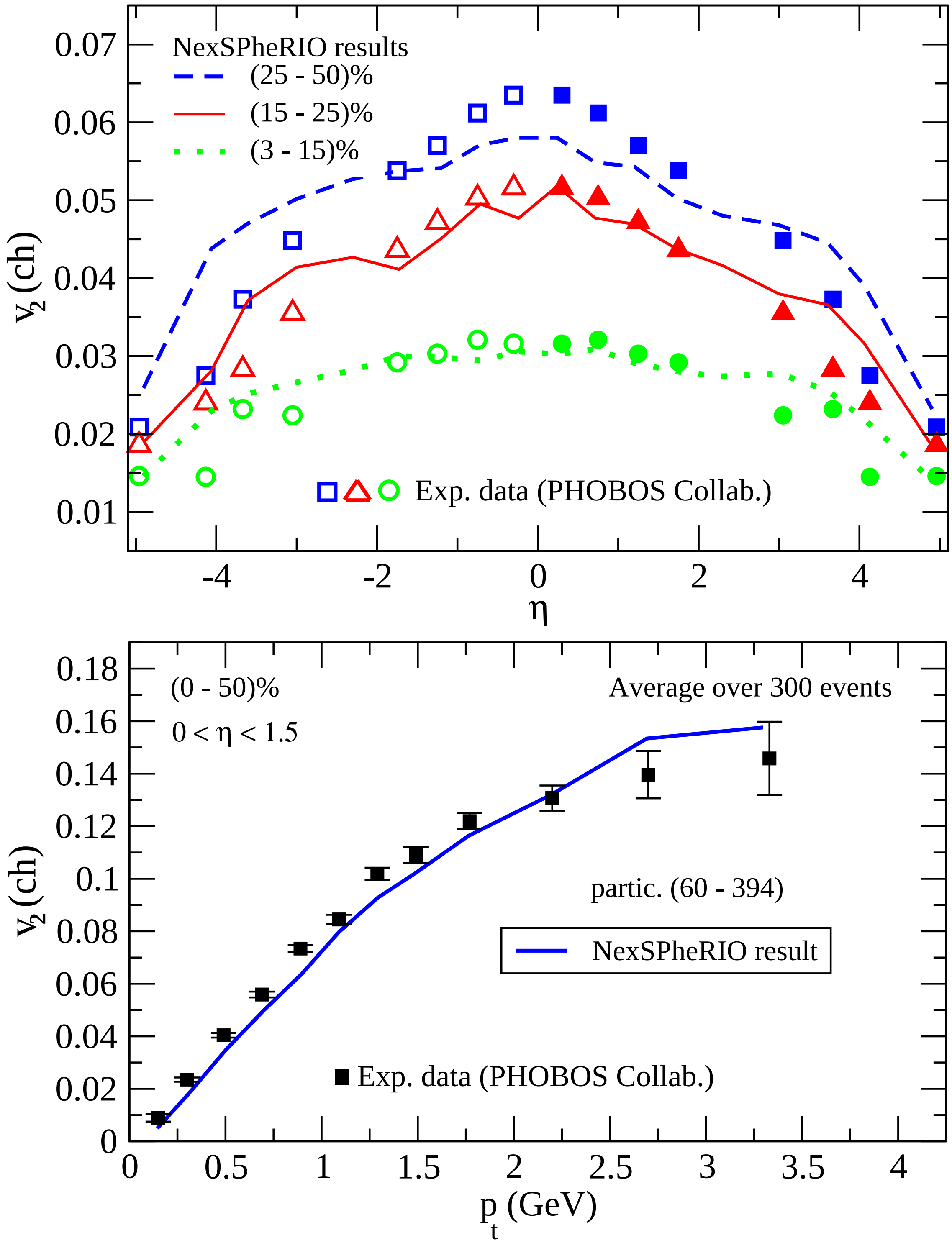


**Figure 5.** $v_2$ computed as explained in the text, compared with PHOBOS data [17]. The upper panel shows the $\eta$ distributions in three centrality windows as indicated. The lower panel shows the $p_T$ distribution at the mid-rapidity region.

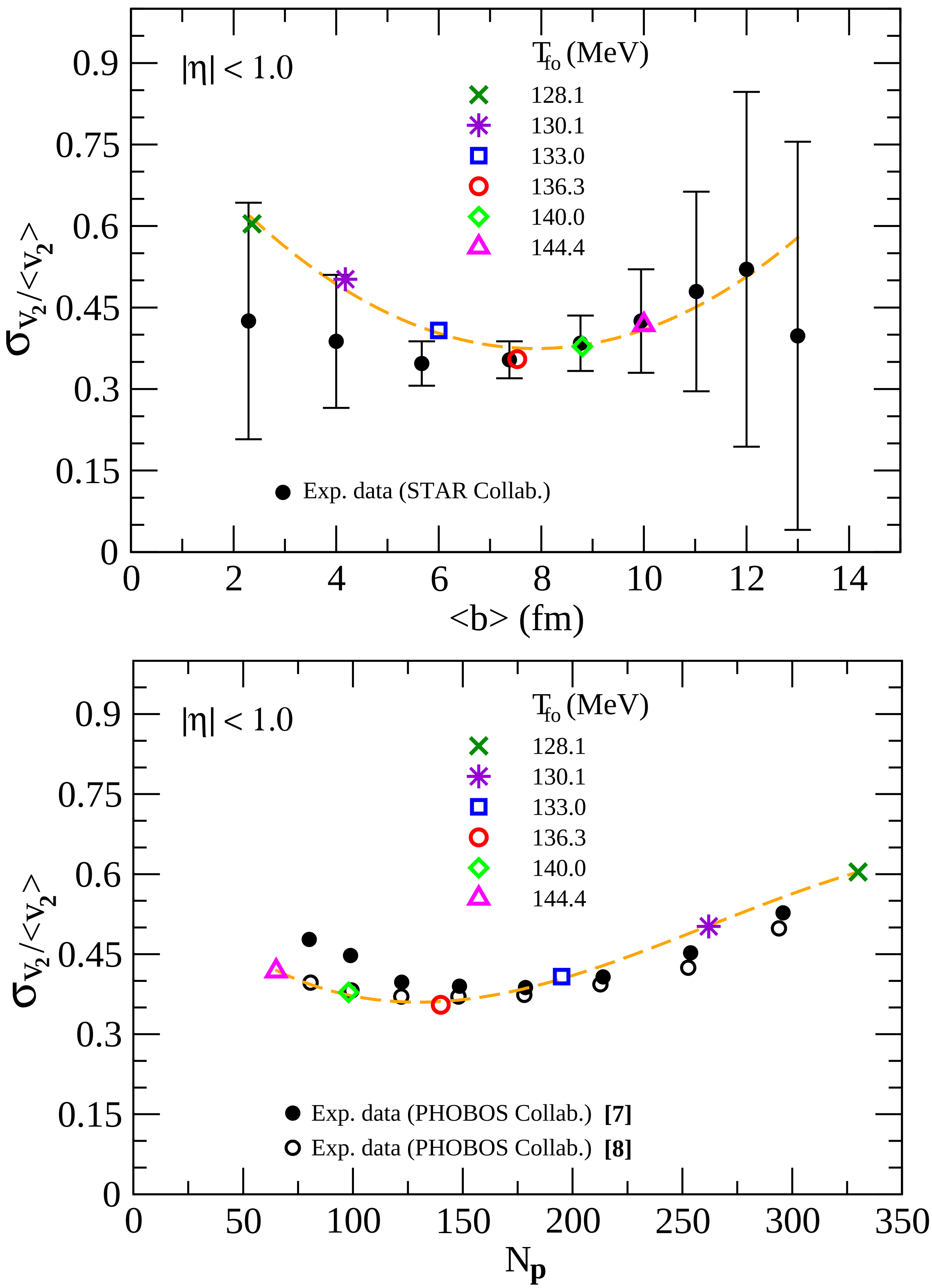


**Figure 6.** $\sigma_{v_2}/\langle v_2\rangle$ computed for Au+Au collisions at 200 $A$ GeV, compared with data. In the upper panel, $\sigma_{v_2}/\langle v_2\rangle$ is given as function of the impact parameter $\langle b\rangle$ and compared with the STAR data [6]. In the lower panel, the same results are expressed as function of participant nucleon number $N_p$ and compared with the PHOBOS data, [7, 8].